

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
9 August 2001 (09.08.2001)

PCT

(10) International Publication Number
WO 01/57473 A1

(51) International Patent Classification⁷: **G01B 21/04, H02K 7/00, 16/00**

(21) International Application Number: **PCT/GB01/00370**

(22) International Filing Date: **31 January 2001 (31.01.2001)**

(25) Filing Language: **English**

(26) Publication Language: **English**

(30) Priority Data:
0002375.4 3 February 2000 (03.02.2000) **GB**

(71) Applicant (for all designated States except US): **RENISHAW PLC [GB/GB];** New Mills, Wotton-under-Edge, Gloucestershire GL12 8JR (GB).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **WESTON, Nicholas, John [GB/GB];** 91 (3F1) Harrison Road,

Edinburgh EH11 1LS (GB). **NAI, Kenneth, Cheng-Hoe [SG/GB];** 89 Warrender Park Road, Edinburgh EH9 1EW (GB). **MCFARLAND, Geoff [GB/GB];** The Manse, 22 Church Road, Upper Cam, Dursley, Gloucestershire GL11 5PG (GB). **MCMURTRY, David, Roberts [GB/GB];** 20 Tabernacle Road, Wotton-under-Edge, Gloucestershire GL12 7EF (GB).

(74) Agent: **WAITE, John;** Renishaw plc, Patent Department, New Mills, Wotton-under-Edge, Gloucestershire GL 12 8JR (GB).

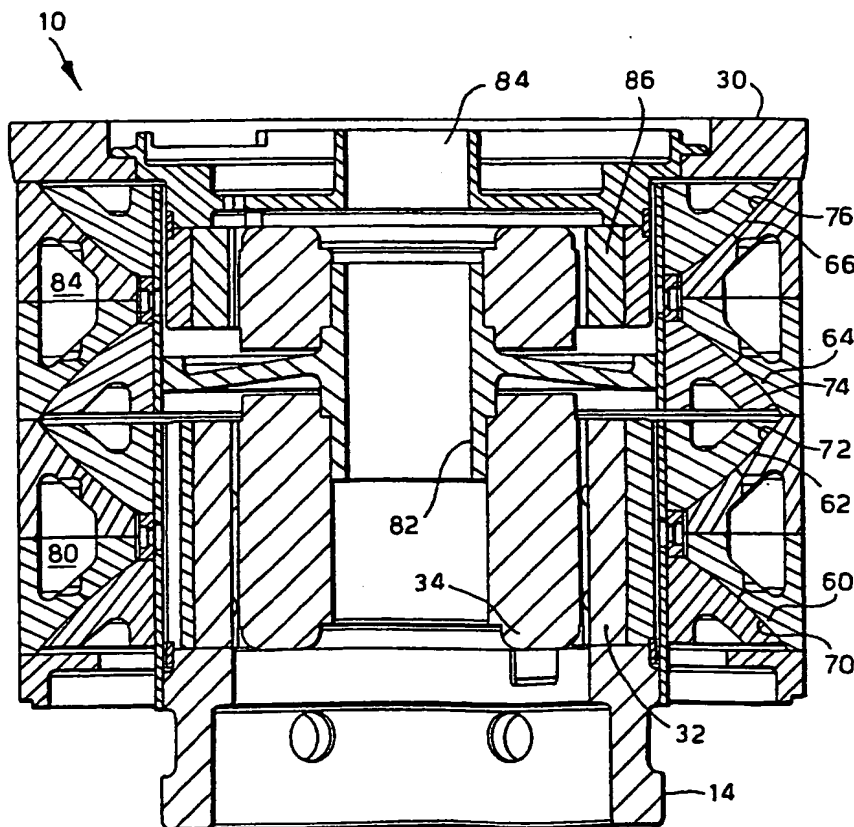
(81) Designated States (national): **JP, US.**

(84) Designated States (regional): European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR).

Published:
— with international search report

[Continued on next page]

(54) Title: **REACTIONLESS ROTARY DRIVE MECHANISM**



(57) Abstract: An articulating probe head includes motors (12 and 18) for driving respective output shafts (14 and 20) about respective orthogonal axes (Z and X) to move a stylus (22) over the surface of a workpiece under the control of a controller (26). At least one of the motors is inertia balanced by mounting the stator (32) of the motor on bearings (42) to allow it to rotate in opposition to the rotation of the rotor (34). Control of the speed of the spinning stator is achieved by connecting it to the winding assembly (46) of an additional "back-to-earth" motor (47), the magnet assembly (48) of which is connected to the housing. The motor (47) acts as a brake to prevent overspeeding of the rotatable stator.

WO 01/57473 A1



For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

REACTIONLESS ROTARY DRIVE MECHANISM

The invention relates to a mechanism for providing reactionless drive to a rotary member of, for example, an articulating probe head which may be mounted on the movable arm of a coordinate positioning machine.

In our US Patent No. 5,189,806 there is described an articulating probe head capable of orienting a probe with two degrees of freedom to enable the probe to be used in an operation for scanning the surfaces of workpieces.

In general, such a probe head includes a rotary drive mechanism having a relatively fixed supporting structure and a rotary member which is rotatable by a motor relative to the supporting structure about an axis of the structure. The motor includes, in the case of an electric motor for example, a stator operably connected to the supporting structure and a rotor operably connected to the rotary member. Torque generated by the motor and applied to the rotary member also causes an equal and opposite reaction torque to be applied to the stator and thus to the supporting structure.

This reaction torque can cause a rotation on the movable arm of the coordinate positioning machine on which the probe head is mounted, leading to errors in the measurements made by the machine.

In the specific example shown in the patent specification referred to, a second rotary drive mechanism is mounted on the output shaft of the first mechanism and rotates a second rotary member about an axis at right angles to the axis of the first rotary mechanism.

Because the articulating probe head described in the above patent specification is required at times to drive a probe mounted on it with an oscillatory motion, in one of the preferred embodiments, the so-called stator is
5 mounted on a bearing to allow it to rotate freely relative to the support structure and the rotor, so that the angular momentum of the rotor is counter-balanced by the freely spinning stator.

10 Thus, when the motor is operated to accelerate the rotary member, the free spinning stator accelerates in the opposite direction reacting to the output rotor torque. Thus there is no natural path back to the static structure to react the rotor output torque, and thus no
15 resultant torque is passed back to the machine on which the head is mounted.

However, there are occasions when it is necessary to control the speed of the rotatable stator. For example,
20 there are opposing torques applied to the spinning stator which create losses in the angular momentum of the stator and which would tend to slow the stator down in a constant angular velocity rotor move. These losses are due to aerodynamic drag on the rotating stator, friction
25 in various parts of the stator assembly, and a back EMF which is created as the stator coils rotate through the magnetic field of the motor. In order to maintain the relative angular speed of the spinning stator, power has to be supplied in some manner to the stator to overcome
30 these losses.

At the same time, external forces applied to the rotor member, such as for example, gravity torque, or a torque produced by the probing force between the probe and a

workpiece, act to slow the rotor down. This causes the control system to supply more power to the motor driving the rotor, to maintain the probing speed, and this additional power tends to then over-speed the freely
5 spinning stator. To overcome this, a mechanism has to be provided which will apply a braking force to the spinning stator.

These problems are overcome in accordance with the
10 present invention by providing an additional motor including a winding assembly and a magnet assembly, one of which is attached to the rotatable stator, and the other of which is attached to the fixed structure of the housing.

15 By this means, the additional motor provides a frictionless braking force on the free spinning stator which increases as the speed of rotation of the stator increases. Also when it is necessary to provide power to
20 the stator to overcome losses, this is achieved by supplying current to the additional motor.

The reactionless behaviour in such a configuration is therefore limited to accelerations of the rotary drive
25 mechanism. Reactions due to external probing etc are transmitted to the mountings of the mechanism, reactions due to rotary accelerations are not.

The invention will now be more particularly described, by
30 way of example only, and with reference to the accompanying drawings in which:

Fig 1 is a diagrammatic representation of an articulating head which incorporates a reactionless rotary drive mechanism of the present invention;

Fig 2 is a diagrammatic representation in cross-section of a reactionless rotary drive mechanism of the present invention;

Fig 3 is a detailed cross-section of one embodiment
5 of a reactionless rotary drive mechanism as incorporated in an articulating head of Fig 1; and

Fig 4 is a block diagram showing the basic elements of the controller used to control the reaction drive.

10 Referring now to the drawings, in Fig 1 there is shown an articulating probe head which comprises a first housing part 10 adapted for attachment to a position determining apparatus (not shown). Housing part 10 contains a rotary drive mechanism of the present invention which includes a
15 motor 12 to provide rotation of an output shaft 14 about a first axis z. Attached to the shaft 14 is a second housing part 16 which contains a second rotary drive mechanism including a motor 18 to provide rotation of a second shaft 20 about a second axis x orthogonal to the
20 first axis z.

Attached to the second shaft for rotation therewith is a surface sensing device 22 which, in a typical scanning operation, is driven over the surface of a workpiece to
25 enable measurements to be made of points on the workpiece surface.

Power is supplied to the rotary drive mechanisms through electrical connections 24, from a controller 26 which is
30 programmed to control the surface sensing device to move over the surface of a workpiece in a desired series of moves. Transducers within the head send signals indicative of the angular positions of the drive mechanisms about their respective axes back to servo

control loops in the controller. These signals together with signals from the measuring devices of the machine on which the head is mounted, enable the relative positions of the surface sensing device and a workpiece surface to be accurately controlled.

As explained above vibrations induced in the machine due to oscillating motions of the surface sensing device and its rotary drive mechanisms are reduced by using an inertia balanced motor in at least one of the rotary drive mechanisms.

Referring now to Fig 2 details of a rotary drive mechanism incorporating the additional motor of the present invention are illustrated diagrammatically by way of example. It is to be understood however, that the following description can be applied to either one, or both of the rotary drive mechanisms of the articulating head.

The mechanism is contained within a housing which includes a flange 30 to enable the housing to be connected to the quill of a measuring machine, or to the housing of the other rotary drive mechanism.

The mechanism shown consists of a main drive motor 12 having a main drive magnet assembly 32 and a main drive winding assembly 34. Power is supplied to the main drive winding assembly through a brush assembly 36 to drive the main drive rotor 38, which in this example, is connected to the main drive winding assembly. The main drive rotor is connected to the output shaft 14 which is mounted for rotation on a bearing 40.

The main drive magnet assembly which would normally form the stator of the motor, is also mounted on a bearing 42, so that when power is supplied to drive the shaft 38, the reaction in the main drive magnet assembly causes this
5 stator assembly to rotate freely on the bearing 42 with an equal and opposite angular momentum.

It can be seen that the motor 12 behaves as a reactionless rotary drive mechanism as far as any rotary
10 accelerations and decelerations are concerned.

The rotating stator assembly, in this example, is connected through a shaft 44 to a winding assembly 46 of an additional "back-to-earth" (BTE) motor 47, the magnet
15 assembly 48 of which is connected to the housing. A further brush assembly 50 is provided to enable power to be supplied to the BTE winding assembly.

Because both parts of the motor are rotatable, the power
20 connections to the motor parts are brought across from the housing through a slip ring assembly 52.

The additional BTE motor provides a reaction force to counter the rotation of the freely rotating stator. This
25 force increases as the speed of the stator increases. Also the brush assembly 50 can be used to supply power to the BTE motor windings to counter the losses which would otherwise tend to slow the stator down when the main motor is running at constant angular velocity.

30

Fig 3 is a cross-section of a preferred embodiment of the invention in which, where possible, the same reference numerals have been used to indicate the same parts.

In this embodiment the rotary drive mechanism is mounted within the housing part 10 of the articulating head of Fig 1 so that the flange 30 is to be connected to the machine quill and the output shaft 14 is to be connected
5 to the second part 16.

The housing part 10 provides part-spherical bearing support surfaces 60,62,64 and 66 for supporting the rotating elements of the drive mechanisms.

10

In this embodiment the main drive magnet assembly 32 of the main drive motor is connected to the output shaft 14, and is supported for rotation on the bearing surfaces 60 and 62 by a pair of oppositely facing part-spherical
15 bearing surface 70 and 72. The surfaces 70 and 72 are shaped to co-operate with the bearing surfaces 60 and 62 to form an air bearing which is supplied with pressurised air through nozzles from a main air duct 80.

20 The main drive winding assembly 34 of the main drive motor is connected by means of a shaft 82 to the winding assembly 84 of a BTE motor, the magnet assembly 86 of which is connected to the housing 10.

25 A pair of oppositely facing bearing surfaces 74 and 76 connected to the shaft 82 support the shaft on the bearing surfaces 64 and 66. Once again the bearing surfaces 74,76 are shaped to co-operate with the bearing surfaces 64,66 to form an air bearing which is supplied
30 with pressurised air from a main duct 84.

The power supply to both the main drive winding assembly and the BTE motor winding assembly is supplied by a brush assembly not shown in this view.

The controller 26 that implements the control strategy for the reactionless drive system has a structure shown in Fig 4. The controller performs two tasks, a) it controls the position of the main drive rotor against an input demand, and b) it controls the speed of the free-spinning stator so as to maintain the reactionless nature of the entire drive system.

Position control of the main drive rotor 38 is achieved using an inner drive rotor speed feedback loop 90 and an outer drive rotor position feedback loop 92. Control action is applied to the inner speed loop in the form of a Proportional-Integral-Derivative (PID) compensator 94, the output of which is passed via an amplifier 96 to the main drive motor 12. Proportional control action is also applied to the positional error in the outer loop, which includes a position loop gain control 89.

Control of the BTE motor is achieved using feedback of the free-spinning stator speed 98. The BTE control loop 100 (the elements of which are enclosed within the dotted boundary), produces a correction signal that generates a torque in the BTE motor so as to eliminate the effects of external torques acting on the main drive rotor. In the presence of an external torque, the speed of the free-spinning stator would diverge from its desired speed. The BTE control loop will generate a torque in the BTE motor to correct the speed difference. The main elements of the BTE control loop are a calculator 102, which calculates the desired speed of the free-spinning stator, a gain control 104, a second order low pass filter 106 and a power amplifier 108.

The torque produced by the BTE motor is proportional to

the difference between the measured speed of the free-spinning stator and its desired speed as described in the following equation;

$$5 \quad T_{rm} = K_{BTE} (\text{Desired Free-Spinning Stator Speed} - \text{Measured Free-Spinning Stator Speed})$$

Where

T_{rm} denotes the torque produced by the BTE motor

$$10 \quad K_{BTE} \text{ denotes the BTE loop gain}$$

The desired speed of the free-spinning stator is calculated using the following equation;

$$15 \quad \text{Desired Free - Spinning Stator Speed} = \left(\frac{\text{Total Inertia on Drive Rotor}}{\text{Total Inertia on Free - Spinning Stator}} \right) \text{Drive Rotor Speed}$$

In a probe system, the total inertia on the drive motor is likely to change both statically (when a probe or stylus is changed) and dynamically (changes in angle of the probe with respect to an orthogonal rotary axis). The inertia of the free-spinning stator is unlikely to change. The desired free-spinning stator speed is calculated in real-time using prior knowledge of inertia values of the physical system. The static inertia values are represented in the form of a look-up table corresponding to the probe and stylus type. The dynamics changes to the drive rotor inertia are implemented in the form of an equation that takes into account the dynamically changing angle of the probe.

30

The BTE control loop is made to have a low bandwidth through the second order low pass filter 106 since fast control action is not essential for controlling the speed of the free-spinning stator. It is desirable to have a

low bandwidth BTE control for two reasons; firstly, during acceleration or deceleration of the main drive motor, the reaction torque generated in the free-spinning stator should not be acted upon by the BTE control loop.

5 BTE control should only be applied to slowly changing speed variations in the free-spinning stator. Secondly, the BTE control loop is a slave to the main drive motor control loop that has a high bandwidth. Should both the control loops have the same bandwidth, there is a chance

10 of undesired interactions between the two loops.

CLAIMS

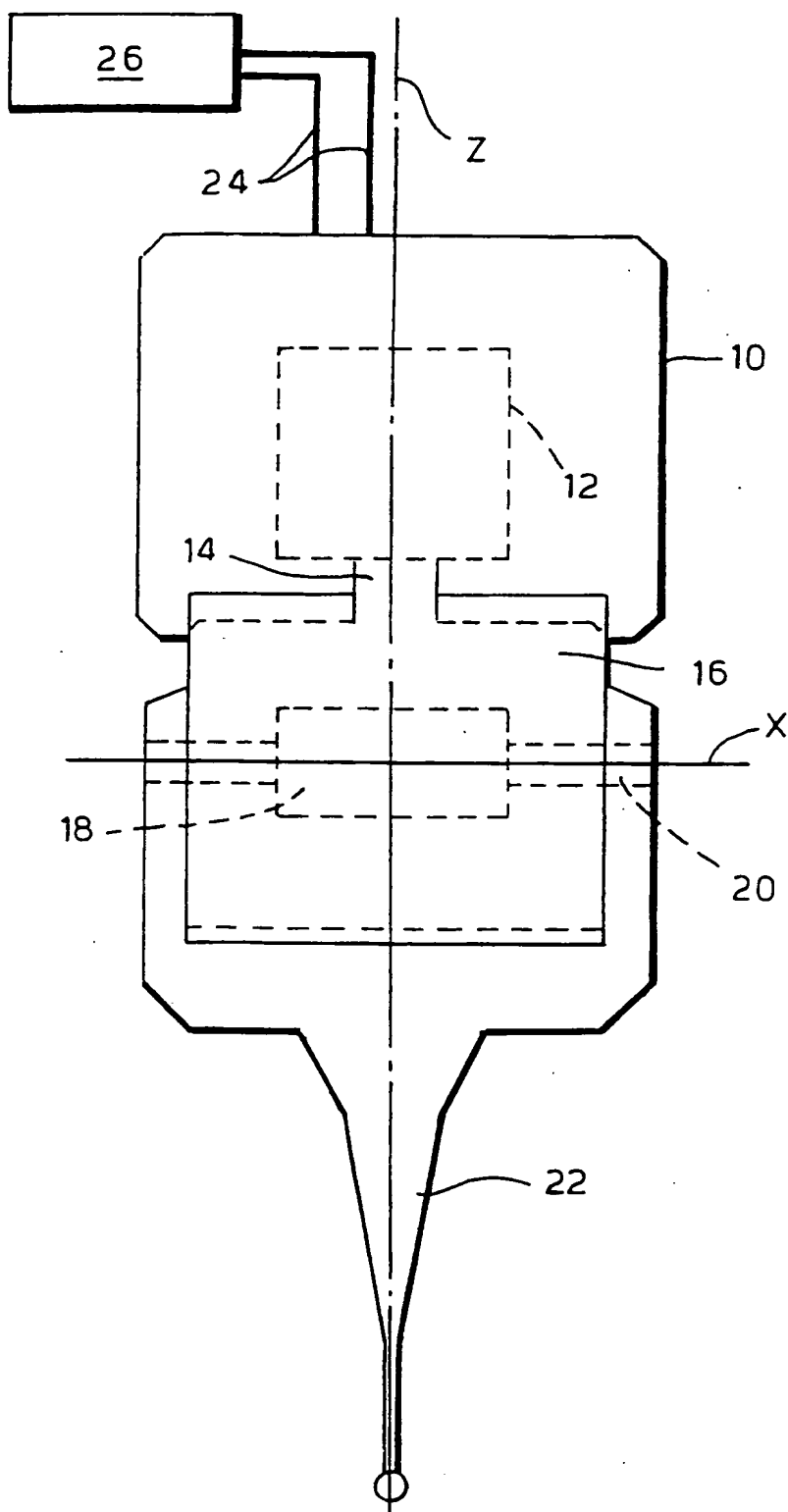
1. A reactionless rotary drive mechanism comprising a first motor, a power supply for supplying power to said
5 motor to drive it, the motor including a rotor, and a rotatable stator mounted from fixed structure on a bearing and which rotates in a direction opposite to that of the rotor at a speed dependent on the speed of rotation of the rotor, wherein a second motor is provided
10 which includes a winding assembly and a magnet assembly one of which is connected to the rotatable stator, the other one of which is connected to the fixed structure on which said bearing is mounted.
- 15 2. A reactionless rotary drive mechanism according to claim 1 wherein means are provided for supplying power to the second motor to counter losses which would tend to slow the speed of rotation of the rotatable stator of the first motor.
- 20 3. A reactionless rotary drive mechanism according to claim 1 wherein the means for supplying power to the first motor comprise slip rings.
- 25 4. A reactionless rotary drive mechanism according to claim 1 wherein a controller is provided for controlling the supply of power to the motors.
5. A reactionless rotary drive mechanism according to
30 claim 1 wherein the first motor is a drive motor of an articulating probe head.
6. A reactionless rotary device mechanism according to claim 5 wherein the fixed structure to which the second

12

motor is connected is a housing of the probe head.

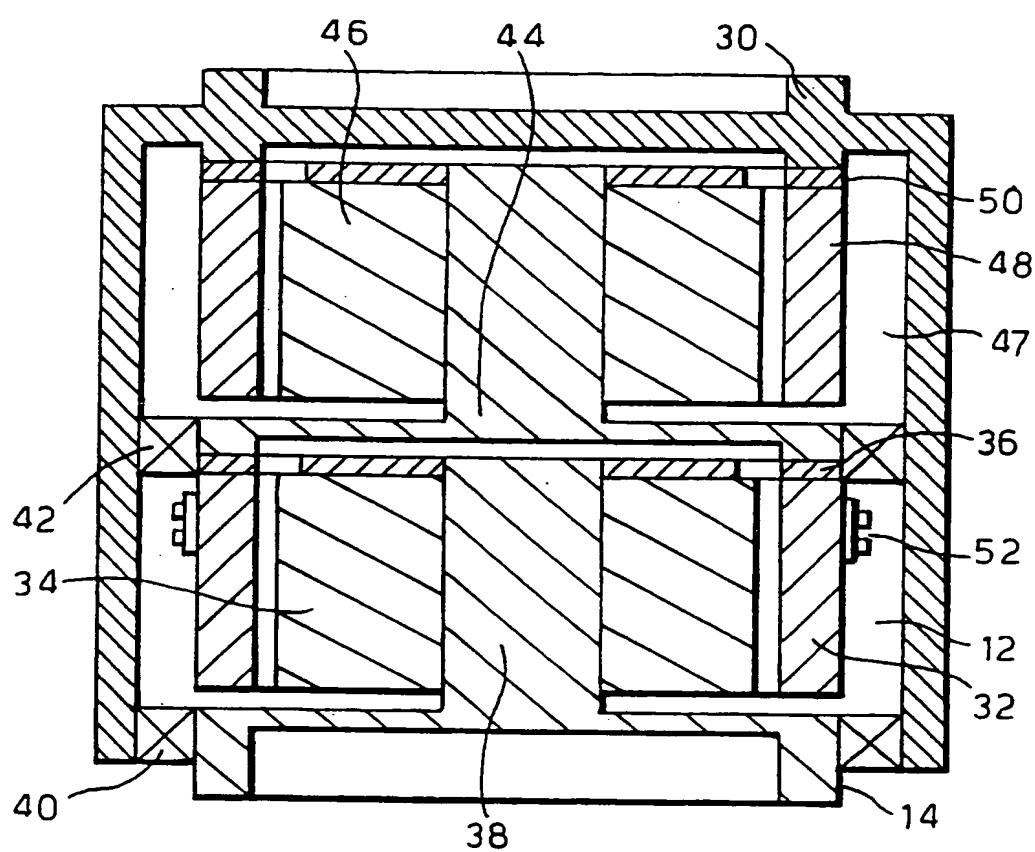
1/4

Fig.1.



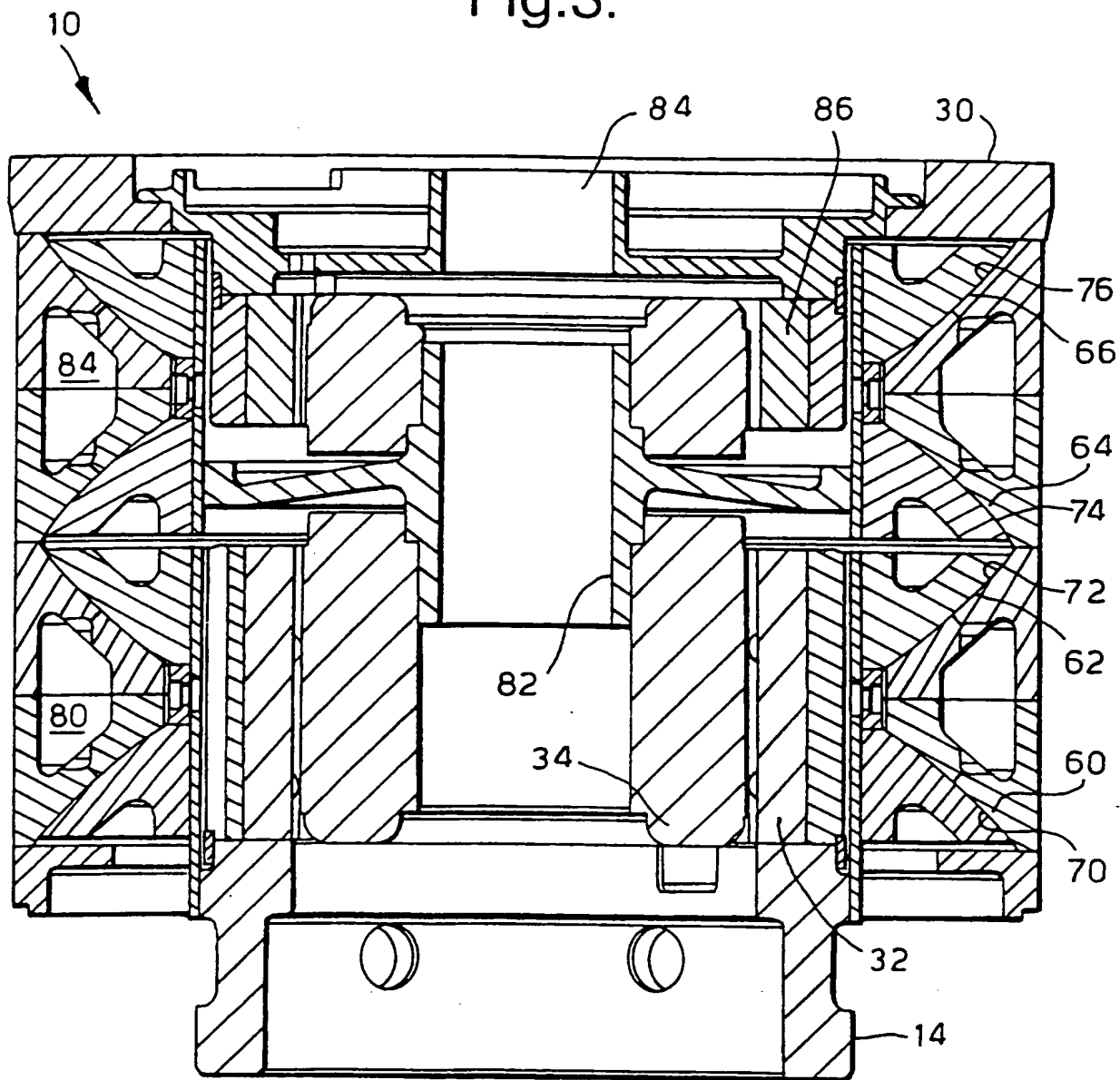
2/4

Fig.2.



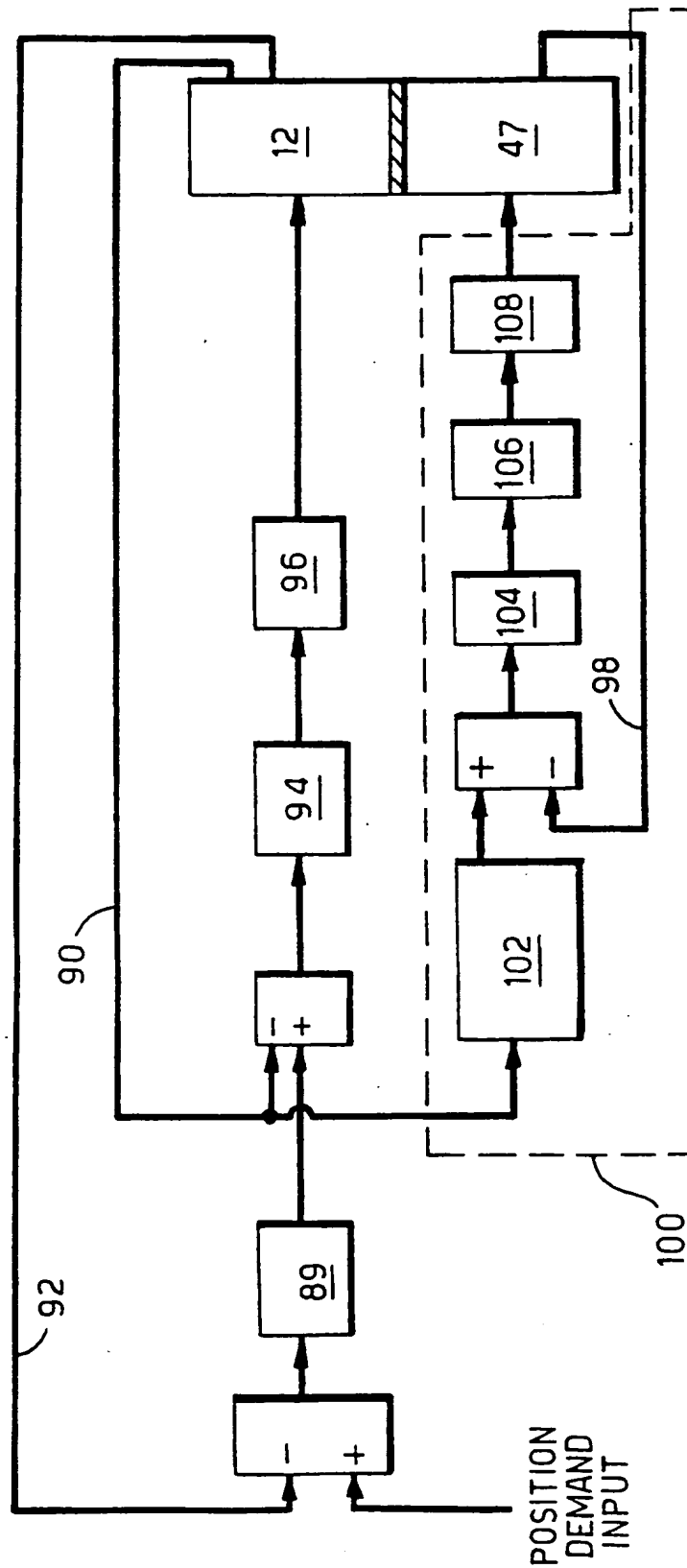
3/4

Fig.3.



4/4

Fig.4.



INTERNATIONAL SEARCH REPORT

International Application No

PC1/GB 01/00370

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G01B21/04 H02K7/00 H02K16/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G01B H02K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 021 716 A (RUE ARTHUR K) 3 May 1977 (1977-05-03) the whole document ---	1-6
X	US 4 375 047 A (NELSON VIRGIL W ET AL) 22 February 1983 (1983-02-22) column 2, line 43 -column 3, line 23; figure 1 ---	1,5,6
A	US 5 063 336 A (ATLAS GERARD) 5 November 1991 (1991-11-05) the whole document ---	1-6
A	US 4 976 163 A (SCHUMACHER LARRY) 11 December 1990 (1990-12-11) the whole document ---	1-6
-/--		



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

* Special categories of cited documents:

- *A* document defining the general state of the art which is not considered to be of particular relevance
- *E* earlier document but published on or after the international filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

- *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- *X* document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- *Y* document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- *Z* document member of the same patent family

Date of the actual completion of the international search

20 April 2001

Date of mailing of the international search report

07/05/2001

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer

Beyfuß, M

INTERNATIONAL SEARCH REPORT

International Application No

PCT/GB 01/00370

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>US 5 189 806 A (MCMURTRY DAVID R ET AL) 2 March 1993 (1993-03-02) cited in the application column 4, line 39 -column 4, line 50; figure 1</p> <p style="text-align: center;">-----</p>	1-6

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PC1/GB 01/00370

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 4021716 A	03-05-1977	CA 1048129 A	06-02-1979
		DE 2554519 A	15-07-1976
		FR 2296164 A	23-07-1976
		GB 1511040 A	17-05-1978
		IL 48326 A	30-11-1977
		IT 1052877 B	20-07-1981
		JP 1079817 C	25-01-1982
		JP 51089077 A	04-08-1976
		JP 56019563 B	08-05-1981
		SE 413943 B	30-06-1980
		SE 7514377 A	24-06-1976
US 4375047 A	22-02-1983	CA 1180377 A	01-01-1985
US 5063336 A	05-11-1991	FR 2642495 A	03-08-1990
		CA 2008306 A	31-07-1990
		DE 69001684 D	01-07-1993
		DE 69001684 T	23-12-1993
		EP 0381575 A	08-08-1990
		ES 2042225 T	01-12-1993
US 4976163 A	11-12-1990	NONE	
US 5189806 A	02-03-1993	DE 3878557 D	25-03-1993
		DE 3878557 T	03-06-1993
		DE 68922990 D	13-07-1995
		DE 68922990 T	07-12-1995
		EP 0402440 A	19-12-1990
		WO 9007097 A	28-06-1990
		JP 2873404 B	24-03-1999

**This Page is Inserted by IFW Indexing and Scanning
Operations and is not part of the Official Record**

BEST AVAILABLE IMAGES

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images include but are not limited to the items checked:

- ☐ **BLACK BORDERS**
- ☐ **IMAGE CUT OFF AT TOP, BOTTOM OR SIDES**
- ☒ **FADED TEXT OR DRAWING**
- ☐ **BLURRED OR ILLEGIBLE TEXT OR DRAWING**
- ☐ **SKEWED/SLANTED IMAGES**
- ☐ **COLOR OR BLACK AND WHITE PHOTOGRAPHS**
- ☐ **GRAY SCALE DOCUMENTS**
- ☒ **LINE(S) OR MARK(S) ON ORIGINAL DOCUMENT**
- ☐ **REFERENCE(S) OR EXHIBIT(S) SUBMITTED ARE POOR QUALITY**
- ☐ **OTHER: _____**

IMAGES ARE BEST AVAILABLE COPY.

As rescanning these documents will not correct the image problems checked, please do not report these problems to the IFW Image Problem Mailbox.